



XPath query containment and rewriting using views

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View-based rewriting of XML queries

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Part I

Introduction

XML and XPath

XML

- XML trees: rooted, ordered, unranked node-labeled trees
- Node labels come from an (in)finite alphabet S .
- We denote with T_S all XML trees over alphabet S .

XPath syntax

- **XPath**: A language for navigating and selecting nodes from XML documents.
- XPath expressions are a sequence of XPath steps:
axis :: nodetest[predicate].
- **axis**: is a forward or backward axis (navigation).
- **nodetest**: is a label or a wildcard.
- **predicate**: is another step relative to the context where defined.

Tree pattern queries (twigs)

- We focus on XPath expressions with only the child and descendant axis.
- We model them as **pattern trees or twigs**.

Pattern tree (twig)

- Each XPath step is a **node** of the tree pattern.
- Steps along child axis are indicated with single lines edges (**child edges**).
- Steps along descendant axis are indicated with double lines edges (**descendant edges**).
- Predicates are denoted as subtrees of the corresponding step.
- The last step of the expression is called **selection node** and is denoted by underlining the nodetest.

Embedding & evaluation of XPath

Embedding

- An **embedding** from an XPath query p to an XML tree t , is a function $e : V_p \rightarrow V_t$, with the following properties:
- **root preserving**: $e(r_p) = r_t$,
- **label preserving**: $\forall n \in V_p$, if $n.label \neq *$, then $n.label = e(n).label$,
- **structure preserving**: $\forall e' = (n_1, n_2) \in E_p$, if e' is a **child** edge then $e(n_2)$ is a child of $e(n_1)$ in t ; otherwise $e(n_2)$ is a descendant of $e(n_1)$ in t .

XPath query evaluation

Given an XPath query p and an XML tree t , $p(t) = \bigcup_{e \in EB} \{(t)_{sub}^{e(o_p)}\}$, where EB is the set of all embeddings from p to t .

Part II

XPath query containment

Introduction

Definition

XPath query p is contained in q , denoted as $p \subseteq q$, if and only if $p(t) \subseteq q(t)$, for every XML tree t . (The definition can be easily extended for the case of a DTD existence).

Theorem

For XPath queries p, q there is a translation to boolean XPath queries p_0, q_0 , such that $p \subseteq q$ if and only if $p_0 \subseteq q_0$ [17]

Techniques for checking containment

- Canonical models
- Homomorphism technique
- Automata technique
- Chase technique

Canonical model technique

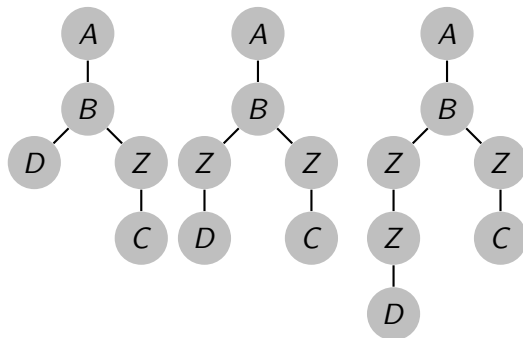
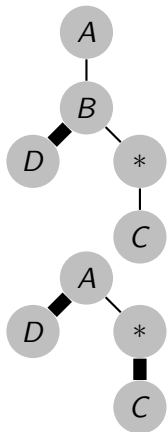
- We consider boolean tree pattern queries p, q .
- Intuition: $p \not\subseteq q$ if and only if there is a counter example XML tree t , such that $p(t) \not\subseteq q(t)$.
- If there is such a counter example it will be in the set of canonical models for p .

Canonical models for XPath query p

- Each canonical model is an XML tree t obtained from p .
- **Wildcards:** replace wildcard nodes in p with a new symbol say z not in p or q .
- **Descendant Edges:** replace a descendant with a chain of at most $m(q) + 1$ z -labeled nodes, where $m(q)$ is the longest chain of child edges with wildcard-labeled nodes in q .

Example

XPath queries P , Q Canonical models for P , $M(Q) = 1$



All of

them match Q , therefore $P \subseteq Q$.

Homomorphism technique

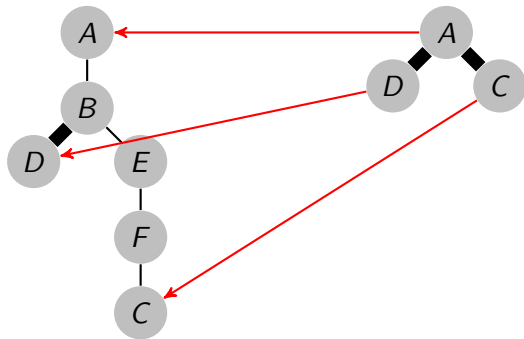
- Given two tree pattern queries p, q then: $p \subseteq q$ if and only if there is a homomorphism from q to p .
- This is not the case for XPath queries in $XP(/, //, [], *)$ where homomorphism is not necessary for containment.

Homomorphism from q to p

- An **homomorphism** from an XPath query q to an XPath query p , is a function $h : V_q \rightarrow V_p$, with the following properties:
- root preserving**: $h(r_q) = r_p$,
- label preserving**: $\forall n \in V_q$, if $n.label \neq *$, then $n.label = h(n).label$,
- structure preserving**: $\forall e' = (n_1, n_2) \in E_q$, if e' is a **child** edge then $h(n_2)$ is a child of $h(n_1)$ in p ; otherwise $h(n_2)$ is a descendant of $h(n_1)$ in p .

Example

Homomorphism from Q to P



There is a Homomorphism from Q to P, therefore $P \subseteq Q$.

Automata technique (1/2)

- Intuition 1: Reduce the containment problem between XPath queries to the containment problem between tree automata or the languages that are accepted by these automata.
- Intuition 2: Compactly represent all counter examples that will imply no containment between two XPath queries and check if it is empty.

Theorem

Containment for XPath expression in $XP(/, //)$ in the presence of a DTD is in PTIME [25, 28]

Proof.

- Construct tree automaton P that accepts trees matching p .
- Construct tree automaton NQ that accepts trees not matching q .



Automata technique (2/2)

Proof.

- Construct tree automaton D that accepts trees conforming to DTD.
- Construct tree automaton $C = P \times NQ \times D$, i.e. the cartesian product of P , NQ , D .
- C accepts all XML trees that conform to DTD and are matched by p but not q .
- Therefore, if C is empty then $p \subseteq q$.
- Every tree automaton construction and checking emptiness of C is in PTIME.



Chase technique (1/2)

- Has been applied on tree pattern queries to obtain PTIME algorithms for containment in the presence of DTDs.
- Considered DTDs **duplicate-free**, **choice-free**.
- Intuition: To decide $p \subseteq q$ extract a set of constraints from DTD, chase query p with the constraints and try to establish a homomorphism from q to p .

Constraints Extracted from a DTD

- **Functional (FC)**: $a \downarrow b$, node a has only one child with label b .
- **Parent-Child (PC)**: $a \rightarrow b$, b when is desc. of a is always child.
- **Sibling (SC)**: $a: B \Downarrow c$, node a with children in B has a c child.
- **Cousin (CC)**: $a: b \Downarrow_c c$, node a with desc. b has also desc. c .
- **Intermediate (IC)**: $a \rightarrow_c b$, c node is always in any path between a , b .

Chase technique (2/2)

Theorem

Let D be a *duplicate-free* DTD and C be the set of SC and FC constraints extracted from D . Let p, q be XPath queries in $XP(/, [])$ then the D -containment $p \subseteq_D q$ can be computed in PTIME using the equivalence:

$$p \subseteq_D q \text{ iff } \text{chase}(p) \subseteq q \text{ [35]}$$

Theorem

Let D be a *acyclic* and *choice-free* DTD and C be the set of SC, PC, IC, CC, FC constraints extracted from D . Let p, q be XPath queries in $XP(/, //, [])$ then the D -containment $p \subseteq_D q$ can be computed in PTIME using the equivalence: $p \subseteq_D q \text{ iff } \text{chase}(p) \subseteq q \text{ [19]}$

Example: chasing an XPath query

- Let $q \equiv /a[b//i][b/d]/j$ be an XPath query in $XP(/, //, [])$.
- Consider the following (duplicate-free, acyclic and choice-free) DTD:

$$a \rightarrow b, f^*, g^+, h$$

$$b \rightarrow (c|d), l$$

$$c \rightarrow i; d \rightarrow i; l \rightarrow j$$

- Apply SC $a: b \Downarrow h$ resulting in $q \equiv /a[b//i][b/d][h]/j$
- Apply FC $a \Downarrow b$ resulting in $q \equiv /a[b[//i][d]][h]/j$
- Apply IC $a \rightarrow_l j$ resulting in $q \equiv /a[b[//i][d]][h]//l//j$
- Apply PC $l \rightarrow j$ resulting in $q \equiv /a[b[//i][d]][h]//l/j$

Part III

XPath query rewriting

XPath query rewriting

- XPath query **rewriting existence** problem: Given an XPath query q and a materialized v , is there any rewriting e of q using v such that for every XML tree t : $e(v(t)) = q(t)$?
- **Finding (minimal) rewriting**: if there is a positive answer to the rewriting existence problem, we seek to find the (minimal) rewriting query e .

Problem Statement

- **Equivalent rewriting**: as defined above.
- **Maximally contained rewriting**: a rewriting e such that for every XML tree t : $e(v(t)) \subseteq q(t)$ and $e(v(t))$ is maximal.

Rewriting existence: compensation pattern (1/2)

Concatenation Operator

- **Concatenation Operator:** $p \oplus q$: an XPath pattern constructed by merging the root of p and the selection node of q into one node.
- Rewriting existence problem: Decide whether an XPath **compensation pattern** q' exists, such that $q' \oplus v \equiv q$.

Theorem

Let q, v be two tree pattern queries with selection nodes as roots, then $q \subseteq v$ iff there exists a rewriting of q using v [37]

Theorem

*The rewriting existence problem is CoNP-Hard for $XP(/, //, [], *)$ [37]*

Rewriting existence: compensation pattern (2/2)

Theorem

*For the subclasses of $XP(/, //, [], *)$ the rewriting existence problem is in PTIME. [37]*

Lemma

*Let v, q be in the subclasses of $XP(/, //, [], *)$, and let n_q be the node in the selection path of q with the same position as the selection node of v at v 's selection path. If a compensation pattern q' of q using v exist, the subpattern of q rooted at n_q (i.e. $(q)_{sub}^{n_q}$) is a compensation pattern of q using v [37]*

Rewriting existence: natural rewriting candidates (1/3)

Natural rewriting candidate

- Let q be a tree pattern query, with $q_{r//}$ we denote the tree pattern obtained from q by turning all edges that emanate from root to be descendant edges.
 - Given a query q and a view v then q' is a **natural rewriting candidate** if is either $(q)_{sub}^{n_q}$ or $((q)_{sub}^{n_q})_{r//}$, where n_q is the node in the selection path of q with the same position as the selection node of v at v 's selection path [2]
-
- What if none natural rewriting candidate is a rewriting of q using v ?
 - Under certain condition a natural rewriting candidate is a **potential rewriting**, that is if a rewriting of q using v exists then one such rewriting is among the two natural rewriting candidates.

Rewriting existence: natural rewriting candidates (2/3)

Conditions for completeness of natural rewriting candidates

- query q :
- if the selection path of q by node n_q has only child edges, then $(q)_{sub}^{n_q}$ is a potential rewriting.
- if $(q)_{sub}^{n_q}$ is **stable** (i.e. the label of root is not wildcard or if the length of the selection path of q is at least 1 and a node emanating from root has unique label in the subtree of q starting under the root node), then it is a potential rewriting.
- **View v :**
- if a descendant edge enters the selection node of v , then $(q)_{sub}^{n_q}$ is a potential rewriting.
- if the selection path of v has only child edges, a potential rewriting exists among the two natural rewriting candidates.

Rewriting existence: natural rewriting candidates (3/3)

Conditions for completeness of natural rewriting candidates

- query q and View v :
- Let q be a tree pattern query and v be a view, such that the last descendant edge on the selection path of q is the k_{th} edge and the k_{th} edge at v selection path is a descendant edge, then $(q)_{sub}^{n_q}$ is a potential rewriting.

Theorem

*The rewriting existence problem for $XP(/, //, [], *)$ under the before mentioned conditions is CoNP-Complete [2]*

Finding minimal rewritings: compensation pattern (1/2)

Theorem

*For the subclasses of $XP(/, //, [], *)$ the problem of finding minimal rewriting is in PTIME [37]*

Proof.

- finding the minimal rewriting of q using v is equivalent of finding the minimal rewriting of the subpattern of q at node n_q (i.e. $(q)_{sub}^{n_q}$) using the subpattern of v at its selection node, say sn_v (i.e. $(v)_{sub}^{sn_v}$).
- Given a query q and a node n , we denote with $q - n$ the subpattern obtained by q by pruning the subpattern of q at node n (i.e. $(q)_{sub}^n$).
- the minimal compensation pattern of q using v is the $(q)_{sub}^{n_q} - R_{(v)_{sub}^{sn_v}}^{(q)_{sub}^{n_q}}$.



Finding minimal rewritings: compensation pattern (2/2)

rewriting Redundant node set R_v^q

- Let q, v be tree pattern queries, such that v 's selection node is its root.
- let n be a node in q then $(q)^n$ is a subpattern of q constructed by adding to the $(q)_n^{sub}$ the root of q and the path, as in q , connecting that root to the root of $(q)_n^{sub}$.
- C_q, C_v are sets including all children nodes of q, v roots respectively.
- $n_q \in C_q$ is **redundant** if there exists $n_v \in C_v$ s.t.
 $(q \oplus v)^{n_q} \equiv (q \oplus v)^{n_v}$.
- R_v^q : set of all redundant nodes.

Proof.

- Computing R_v^q and checking pattern equivalence is in PTIME.



Finding natural rewriting candidates: using stability

Generalized Normal Form (GNF)

Given a tree pattern query q with d nodes on its selection path. Then q is in $GNF_{/*}$ if for all $1 \leq i \leq d$ one of the following holds:

- A child edge enters the i node of q .
- The subpattern of q at the i_{th} node is stable.
- The subpattern of q at the i_{th} node forms a path (not a tree).

Theorem

if q is in $GNF_{/}$, then at least one of the natural rewriting candidate is a potential rewriting [2]*

Finding natural rewriting candidates: looking only for the last descendant

Theorem

if the deepest descendant on the selection path of view v is at least as deep as the deepest descendant on the selection path of the query q , then $(q)_{sub}^{n_q}$ is a potential rewriting, where n_q is the node in the selection path of q with the same position as the selection node of v at v 's selection path [2]

Pattern extension

Let q be a tree pattern query and l be a label, then the l -extension of q denoted with q^{+l} is obtained:

- Add a wildcard labeled child to every leaf of query q , but the selection node (in case it is leaf).
- Add a l labeled child to the selection node of q .

Finding natural rewriting candidates: pattern extension & output lifting

Output Lifting

Let q be a tree pattern query with d nodes on its selection path. Let $1 \leq j \leq d$, then the **output lifting** of q denoted with $q^{j \rightarrow}$ is obtained: from q by considering as selection node the j node on the selection path of q .

Theorem

Let q, v be tree pattern queries and for some $k \leq j \leq d$, where k is the number of nodes in v selection path and d the corresponding for q , the j node of q selection path is not wildcard labeled, then:

- *there is a rewriting of q using v iff there is a rewriting of $(q^{+m})^{j \rightarrow}$ using v^{+*} .*
- *$(q^{+m})^{j \rightarrow}$ using v^{+*} has a rewriting among natural candidates iff so do for q, v [2]*

Form of the rewriting

- Given a query q and a view v with one selection node we saw that the rewriting of q using v is **one** pattern that is formulated by combining a rewriting pattern with v .
- The question is whether the rewriting can be expressed as the **union** of tree pattern queries.
- The answer is **no**!

Theorem

Let q, v be tree pattern queries, then any equivalent rewriting of q using v will contain only one tree pattern query [33]

A general framework for XPath/query rewriting (1/2)

- Let q and v be a tree pattern query and a view respectively with **more than one** node as selection node.
- A rewriting of q using v is a mapping from the selection nodes of q to the selection nodes of v , called **selection node mapping (SNM)**.
- A rewriting is **correct** iff we can use it to establish an embedding from q to any XML tree t , utilizing also the embedding from v to t .
- Let L be the number of nodes in the longest star-path of q and m be the number of descendant edges in q .

A General Framework for XPath query rewriting (2/2)

\vec{u} Extension of Q

Let $\vec{u} = \langle u_1, \dots, u_m \rangle$, where for all $1 \leq i \leq m$, $u_i \geq 0$ and z be a label not in q . Then the \vec{u} extension of q is an XML tree obtained from q as:

- replace all wildcard labeled nodes with the z label.
- replace the i_{th} descendant edge with a path containing u_i z labeled nodes.

Theorem

A rewriting of q using v is correct iff it is correct on the \vec{u} extension of q for all $\vec{u} = \langle u_1, \dots, u_m \rangle$, where for all $1 \leq i \leq m$, $u_i \leq L + 1$ [29]

Maximally contained rewriting: MCR existence

Useful Embedding

An embedding e from q to v is **useful** provided:

- e is empty and the root of q is qualified with the descendant axis.
- **OR** (a) Each node in the selection path of q (if mapped) is mapped to a node in the selection path of v
- **and** (b) For each path p in q **either** p is fully mapped by e **or** if x is the last node in p , where e is defined, and y is its successor node, then x is mapped to the selection node of v or to a descendant of that node or the edge between x, y is descendant.

Theorem

Let q, v be two tree pattern queries, then a MCR of q using v exists iff there is a useful embedding from q to v [19]

Maximally contained rewriting: MCR generation (1/2)

Clip-away tree (CAT)

Given a useful embedding e from q to v , the CAT is obtained as follows:

- Find the **terminal nodes** in q , i.e. nodes x s.t. $e(x)$ is defined and x has at least one child y , where $e(y)$ is not defined.
- For each child y of every terminal node x in q **create a tree pattern** connecting a dummy root to the subtree of q rooted at node y (i.e. $(q)_{sub}^y$) with an edge of the same type (child or desc.) as the edge between x and y in q .
- **Merge** the dummy roots of all the above tree patterns and **label** that root with the label of the selection node of v .

Maximally contained rewriting: MCR generation (2/2)

Algorithm

- ① Compute all useful embeddings from q to v .
 - ② Prune the set of useful embeddings with embeddings that will lead to redundant rewritings [19]
 - ③ Produce the set of CATs that correspond to each of useful embedding.
 - ④ The MCR is the union of the tree patterns (contained rewriting, CR) that are in the set of CATs.
- The algorithm is **exponential**.
 - Note that the MCR is expressed as the **union of CRs** that are tree pattern queries.

Part IV

XPath query rewriting under integrity constraints

Motivation

- Let $q \equiv /a//c$ be an XPath query and $v \equiv /a//b$ be a view in $XP(/, //)$.
- Consider the following (duplicate-free, acyclic and choice-free) DTD:

$$a \rightarrow d, e, f$$

$$d \rightarrow b; b \rightarrow c$$

$$c \rightarrow i; e \rightarrow i; f \rightarrow i$$

- The compensation pattern $e \equiv /b//c$ can be used to rewrite q using v .
- To compute e we need to **chase** query q with the IC $a \rightarrow_c b$.
- Therefore, $q \equiv /a//c \equiv /a//b//c$.
- Note that $e \equiv (q)_{sub}^b$.

Motivation

- Constraints **enable rewritings** in cases for which there would be no rewriting without the constraints.
- In what follows there is a **direct reduction** of the rewriting techniques of the schemaless case under the DTD existence.
- Some DTDs allow PTIME extraction of constraints and PTIME chase:

PTIME cases For DTDs

- **Duplicate-free (DF) DTD**: At each right-hand side of any DTD rule each element name n appears at most once.
- **Acyclic & choice-free (ACF) DTD**: At each right-hand side of any DTD rule there is no alternation. Also, there is no recursion in the DTD.

Equivalent rewriting for $XP(/, [], *)$ under DF DTDs

- Given a query q and a view v in $XP(/, [], *)$ under a DF DTD.
- Applying the **compensation pattern** technique we can answer the rewriting existence problem and find a (minimal) rewriting.
- Though, this technique requires to be able to decide **containment** between tree patterns in this setting.

Theorem

*Containment of queries in $XP(/, [], *)$ in the presence of a duplicate-free DTD is CoNP-hard [24]*

- Two approaches:
incomplete but efficient
complete but exponential

Equivalent rewriting for $XP(/, [], *)$ under DF DTDs

PTIME containment

- Extract SC and FC constraints from DTD.
- Extend them to the wildcard case, resulting in **WSC** and **WFC** constraints.
- Define the **SIC** (single child constraints) and the **WSIC** as a stronger version of the FC, that capture some cases not captured by FCs.
- Decide containment using the **chase** technique based on the following theorem:

Theorem

Let D be a duplicate-free DTD and C be the set of (W)FCs, (W)SCs, (W)SICs implied by D , then $q \subseteq_{\text{SAT}(D)} p$ iff $\text{chase}_C(q) \subseteq p$, if $\text{chase}_C(q)$ is 1-1 homomorphic to a subtree in $\text{SAT}(D)$ (i.e. all trees conforming to D) [4]

Equivalent rewriting for $XP(/, [], *)$ under DF DTDs

- Chasing with (W)SC, (W)FC and (W)SIC constraints a tree pattern in $XP(/, [], *)$ will not always yield a tree pattern 1-1 homomorphic to a subtree in $SAT(D)$.
- There is no set of constraints that can guarantee that [4].

Complete containment

- Intuition: reduce query q into $XP(/, [])$ utilizing the DTD D , so that $chase_C(q)$ is always 1-1 homomorphic to a subtree in $SAT(D)$ [35].
- Therefore, we can decide the containment $q \subseteq_{SAT(D)} p$.
- However, reduction of q from $XP(/, [], *)$ to $XP(/, [])$ by eliminating wildcard is **exponential** [4]

Maximally contained rewriting for $XP(/, //, [])$ ACF DTD: MCR existence

- A **direct application** of the useful embedding as in the schemaless case will not work.
- The reason is that the CAT induced by the embedding composed with the view might result to an **unsatisfiable** rewriting w.r.t. the ACF DTD.

Useful embedding DTD case

An embedding e from q to $chase_C(v)$, where C is the set of PC, SC, FC, CC, IC constraints implied from a ACF DTD D , is **useful** provided:

- is a useful embedding as in the schemaless case.
- **AND** For each node x in q that is not mapped by e , then there is a way in D starting from a rule that carries the label of the selection node of v to produce a node labeled as x .

Maximally contained rewriting for $XP(/, //, [])$ ACF DTD: MCR existence

Theorem

Let q, v be two tree pattern queries and D be an ACF DTD, then a MCR of q using v exists iff:

- ① there is a *useful embedding* from q to $\text{chase}_C(v)$, where C is the set of constraints implied from D
- ② the rewriting composed by the CAT induced by this embedding and the view v is *satisfiable* under D [19]

Maximally contained rewriting for $XP(/, //, [])$ ACF DTD: MCR generation

Algorithm

- ① Extract constraints C implied by ACF DTD D .
 - ② Chase v with only the appropriate constraints from C as to establish a useful embedding from q to $chase_C(v)$.
 - ③ Compute **useful embeddings** and prune this set to avoid redundant rewritings.
 - ④ Produce **the set** of CATs for each of useful embedding.
 - ⑤ The MCR **is the union** of the tree patterns (contained rewriting: CR) that are in the set of CATs [19]
- The algorithm will yield at most one useful embedding and therefore the MCR consists of only **one** tree pattern.
 - Note that there is no need to chase v with every constraint in C (for details see [19]).

Extensions to equivalent rewriting

Immediate Consequences of the previous techniques

- Equivalent query rewriting and containment for queries and views in $XP(/, [], *)$ are in PTIME under ACF DTD.
- Equivalent query rewriting for queries and views in $XP(/, //, [])$ is in PTIME under ACF DTD.

Part V

XPath/XQuery rewriting using multiple views

Introduction

- Hidden hypothesis in the *single-view* rewriting context: the query cache (view) stores only copies of XML elements.
- Using **multiple** views in query rewriting allows exploiting node identifiers from the original XML tree to combine views.
- Given a query q and a set of views V , we seek to find a rewriting r obtained by **intersecting** materialized views in V .
- There is no interest in examining the **union** of these views due to the following theorem:

Theorem

If a tree pattern is equivalent to a union of tree patterns, then it is equivalent to a member of the union [12]

DAG pattern rewriting for $XP(/, //, [])$

Tree patterns extend to DAG patterns, representing the intersection of a set of views.

DAG pattern

- For each view v the $dag(v)$ is the tree pattern corresponding to v .
- $dag(v_1 \cap v_2)$ is obtained by coaleasing the roots and selection nodes of $dag(v_1)$ and $dag(v_2)$, provided there is no label conflict.

Theorem

Any DAG pattern is equivalent to the union of its *interleavings* [12]

DAG pattern rewriting for $XP(/, //, [])$

Definition

Interleaving of a DAG pattern d is a tree pattern p_i whose selection path corresponds to a path in d from its root to its selection node (MB path) **and** if a predicate s appears below node n in MB path, then it also appears below the corresponding node n' in p_i 's selection path.

Algorithm for finding a rewriting

- ➊ Test equivalence from dag pattern d to query q (the opposite is trivial).
- ➋ Compute interleavings p_i from d (d is equivalent to their union).
- ➌ Test union-freeness, i.e. only one interleaving p such that $p \equiv q$. (rule based procedure that transforms d)
- ➍ The rewriting is $(q)_{sub}^n$, where n is the selection node of p [12]

Structural join rewriting for $XP(/, //, [], *)$

- A different approach based on **view selection** for rewriting a query using multiple views.
- How do we produce the set of views V to rewrite q ? **Use automata on tree patterns.**
- Then we can find compensation patterns for each view separately and then **join** the results from applying these patterns to the materialized XML fragment of the corresponding views.
- **Limitations:** We need algorithms to perform these joins **and** most of these algorithms impose certain encodings in the XML trees.

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